Continuous Lower Energy, Emissions and Noise (CLEEN) Program

Aircraft Technology - CLEEN Update

Presented to: REDAC Environment & Energy Subcommittee

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Outline

- CLEEN Program Overview
- CLEEN Phase II Overview
- CLEEN Phase II Technologies
- CLEEN III Notional Timeline
- Summary

CLEEN Program Overview

- CLEEN is FAA's principal environmental effort to accelerate development of new aircraft and engine technologies and advance the introduction of alternative jet fuels.

- Helps achieve the Next Generation Air Transportation System (NextGen) goal of attaining environmental protection that allows sustained aviation growth.

CLEEN Program Overview

CLEEN Phase I (2010-2015)

- Industry partners: Boeing, General Electric, Honeywell, Pratt & Whitney, Rolls-Royce
- Federal Funding: $125M (1:1 minimum cost share is required)

CLEEN Phase II (2015-2020)

- Industry partners: Aurora Flight Sciences, Boeing, Delta/MDS/America's Phenix, General Electric, Honeywell, Pratt & Whitney, Rohr/UTC Aerospace Systems, and Rolls-Royce
- Federal Funding: $100M (1:1 minimum cost share is required)

CLEEN Fact Sheet (updated 2/12/18)

- https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=22534

CLEEN Phase I Benefits:

Demonstrated technologies that reduce noise, emissions and fuel burn

Boeing

Adaptive Trailing Edge
~ 2% fuel burn reduction
~ 1.7 EPNdB cum in some single and twin aisles

CMC Acoustic Nozzle
~ 1% fuel burn reduction
~2.3 EPNdB cumulative noise margin to Stage 4

Honeywell

Fuel Burn Technologies
CLEEN technologies contributed to ~5% fuel burn reduction as part of a 15.7% fuel burn reduction engine package

Pratt & Whitney

Geared Turbofan Technologies
CLEEN techs expand design space for engine with ~ 20% fuel burn reduction, > 20 EPNdB cumulative noise margin to Stage 4

For more information: http://www.faa.gov/go/cleen

General Electric

TAPS II Combustor (entered fleet in 2016)
> 60% margin to CAEP/6 LTO NOx was achieved

FMS/Engine and FMS/ATM Integration (Entered into service - LEAP engine on B737MAX, Airbus A320 Neo aircraft, and GE9X engine on 777X)
0.7-1.0% fuel burn reduction

Open Rotor
~26% reduction in fuel burn (re: 737-800)
~15-17EPNdB cumulative noise margin to Stage 4

Rolls Royce

Ceramic Matrix Composite Turbine Blade Track
CMC blade tracks offer > 50% reduction in cooling flow and component weight.

Rolls-Royce – Dual Wall Turbine Airfoil
Dual Wall turbine airfoils provide > 20% reduction in cooling flow and increased operating temperature capability.

CLEEN tech will provide ~1% fuel burn reduction

CLEEN & Boeing EcoDemonstrator

- **Boeing Quiet Technology Demonstrator Program (2001 & 2005)**
- **CLEEN I began in 2010**
- **"EcoDemonstrator Program formally began in 2011 in cooperation with American Airlines and the FAA" (Boeing Backgrounder – June 2017)**
  http://www.boeing.com/resources/boeingdotcom/principles/environment/pdf/Backgrounder_ecoDemonstrator-2017.pdf
  - 2012: Boeing/CLEEN I flight demonstration of Adaptive Trailing Edge (ATE) system on pre-delivered American Airlines 738-800
  - 2014: Boeing/CLEEN I flight demonstration of Ceramic Matrix Composite (CMC) engine nozzle on 787.
- **"CLEEN is foundational element & enabler for ecoDemonstrator" (Boeing: Nov 2012 CLEEN I Consortium Public Session)**

Assessment of CLEEN Technologies

PARTNER Project 36 (Georgia Tech)

- Environmental Design Space (EDS) used to provide independent assessment of technologies (leveraged PARTNER Project 14 and NASA efforts)
- Modeled most, but not all CLEEN Technologies. Did not model all GE technologies
  - Open rotor engine
  - Engine control/flight management system integration
  - Flight management system/air traffic management integration

Follow-on Efforts

- ASCENT Project 10 (GeorgiaTech-Stanford-Purdue) – evaluating all CLEEN technologies for CO_2, NO_X and noise
- ASCENT Project 37 (GT) CLEEN II Technology Evaluation

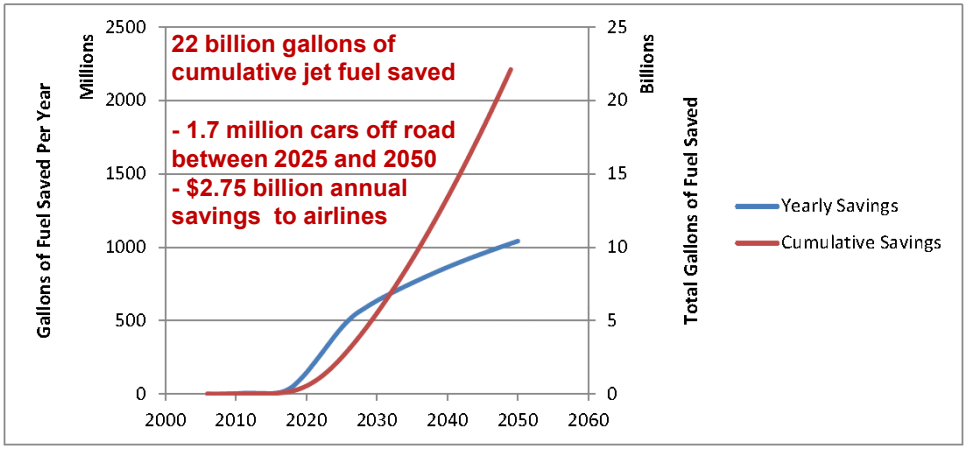


FIGURE 40: POTENTIAL FUEL BURN SAVINGS PROVIDED BY CLEEN TECHNOLOGIES MODELED IN THIS STUDY

PARTNER Project 36 report can be downloaded at:
http://partner.mit.edu/sites/partner.mit.edu/files/PARTNER-Project-36-final-report.pdf

Evaluation of Noise Reductions through CLEEN Technologies

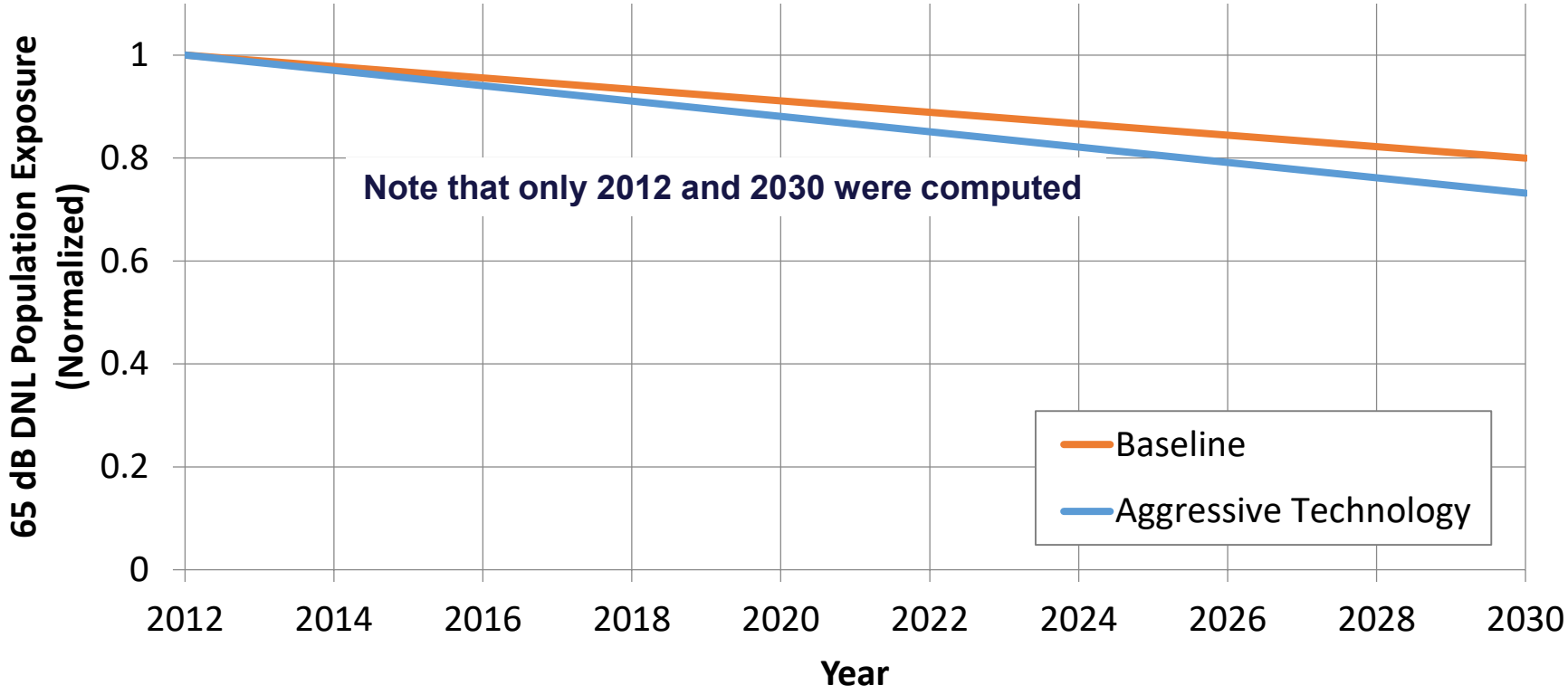
- Adapted from PARTNER Project 36: EDS Assessment of CLEEN Technologies
- CLEEN-funded technologies as well as other public domain and proprietary industry technologies potentially available in the CLEEN timeframe, including NASA N+1 and N+2 technologies

Scenario	Description
Evolutionary (Baseline)	'Normal' technology evolution. Conservative inclusion of CLEEN technologies in N+1.
Aggressive	Represents higher rate of technology development. Includes all CLEEN Techs in N+1

Note:
Additional analysis details and results were given to REDAC in August 2016 in briefing given by Grandi and Dorbian (2016 Aug 30 1:45 pm timeslot)

Impact on Population Exposure to DNL 65

- 20 and 26% decrease in population exposure between 2012 and 2030 for 65 dB contour for baseline and aggressive technology scenarios, respectively.
- 8.5% difference between Baseline and Aggressive Technology in 2030.



Note:
Additional analysis details and results were given to REDAC in August 2016 in briefing given by Grandi and Dorbian (2016 Aug 30 1:45 pm timeslot)

Federal Aviation Administration

CLEEN Phase II Overview (1 of 2)

- **Purpose:**
  - Mature previously conceived noise, emissions and fuel burn reduction technologies for civil subsonic airplanes from Technology Readiness Levels (TRL) of 3-5 to TRLs of 6-7 to enable industry to expedite introduction of these technologies into current and future aircraft and engines
  - Assess the benefits and advance the development and introduction of “drop-in” alternative jet fuels, including blends

- CLEEN II technologies expected to be on a path for introduction into commercial aircraft by 2026

CLEEN Phase II Overview (2 of 2)

CLEEN Phase II Program Details:

- Reducing environmental impacts via aircraft technology and alternative jet fuels
- Five year effort to accelerate technology maturation ***(2015-2020)***
- 50% cost share; total FAA budget: ***~$100M***

CLEEN Phase II Program Goals:

- **32 dB**[1] cumulative noise reduction
- **70%**[2] landing/take-off NOx emissions reduction
- **40%**[1] fuel burn reduction

Conducting ground and/or flight test demonstrations of certifiable aircraft technologies with entry into service by ***2026***

Based on 5-year cost share agreements with industry

Awardees:

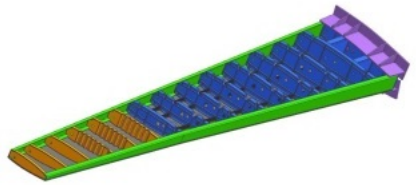
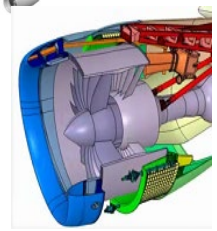
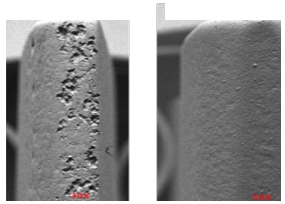
- Aurora Flight Sciences
- Boeing
- Delta Tech Ops, America's Phenix, MDS Coating Technologies
- General Electric (GE) Aviation
- Honeywell Aerospace
- Pratt & Whitney
- Rolls-Royce
- Rohr, Inc. / UTC Aerospace Systems

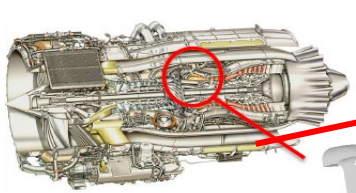
[1] Common baseline with CLEEN I goals

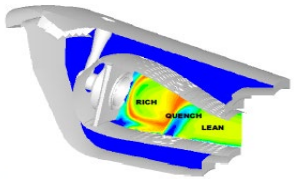
[2] 70% reduction in landing and take-off NOx relative to CAEP/8 standard. Relative to CLEEN I baseline of CAEP/6 this is a 75% reduction.

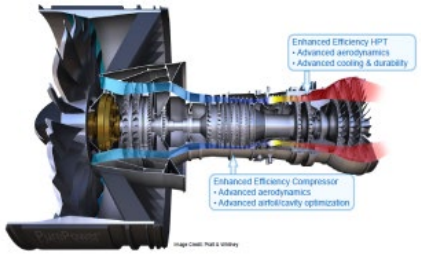
CLEEN Phase II 14 Technologies

- Aurora Flight Sciences: D8 Double Bubble Fuselage
- Boeing: Structurally Efficient Wing (SEW)
- Boeing: Compact Nacelle – Short Inlet
- Delta Tech Ops/MDS Coating Technologies/America's Phenix: Leading Edge Protective Blade Coatings
- GE: TAPS III Combustor
- GE: FMS Technologies
- GE: More Electric Systems and Technologies for Aircraft in the Next Generation (MESTANG)
- GE: Low Pressure Ratio Advanced Acoustics
- Honeywell: Compact Combustor System
- Honeywell: Advanced Turbine Blade Outer Air Seal (BOAS) System
- Pratt & Whitney: High Pressure Compressor Aero-Efficiency Techs
- Pratt & Whitney: High Pressure Turbine Aero-Efficiency & Durability Techs
- Rolls Royce: Advanced RQL Low NOx Combustion System
- UTAS: Thrust Reverser Technology







CLEEN Phase II Goal Impact

Technology	Goal Impact		
	Fuel Burn	Emissions	Noise
Aurora Flight Sciences: D8 Double Bubble Fuselage	✓		✓
Boeing: Structurally Efficient Wing (SEW)	✓		
Boeing: Compact Nacelle – Short Inlet	✓		
Delta Tech Ops; MDS Coating Technologies; America's Phenix: Leading Edge Protective Blade Coatings	✓		
GE: TAPS III Combustor		✓	
GE: FMS Technologies	✓		
GE: More Electric Systems and Technologies for Aircraft in the Next Generation (MESTANG)	✓		
GE: Low Pressure Ratio Advanced Acoustics			✓
Honeywell: Compact Combustor System	✓	✓	
Honeywell: Advanced Turbine Blade Outer Air Seal (BOAS) System	✓		
Pratt & Whitney: High Pressure Compressor Aero-Efficiency Techs	✓		
Pratt & Whitney: High Pressure Turbine Aero-Efficiency & Durability Techs	✓		
Rolls Royce: Advanced RQL Low NOx Combustion System		✓	
UTAS: Thrust Reverser Technology	✓		✓

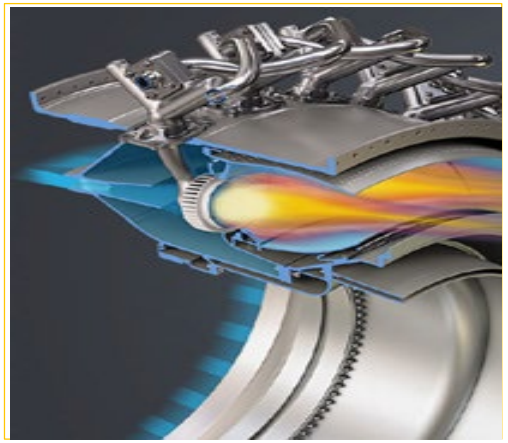
Technology & Emissions Reduction

- Visible smoke emissions have been eliminated

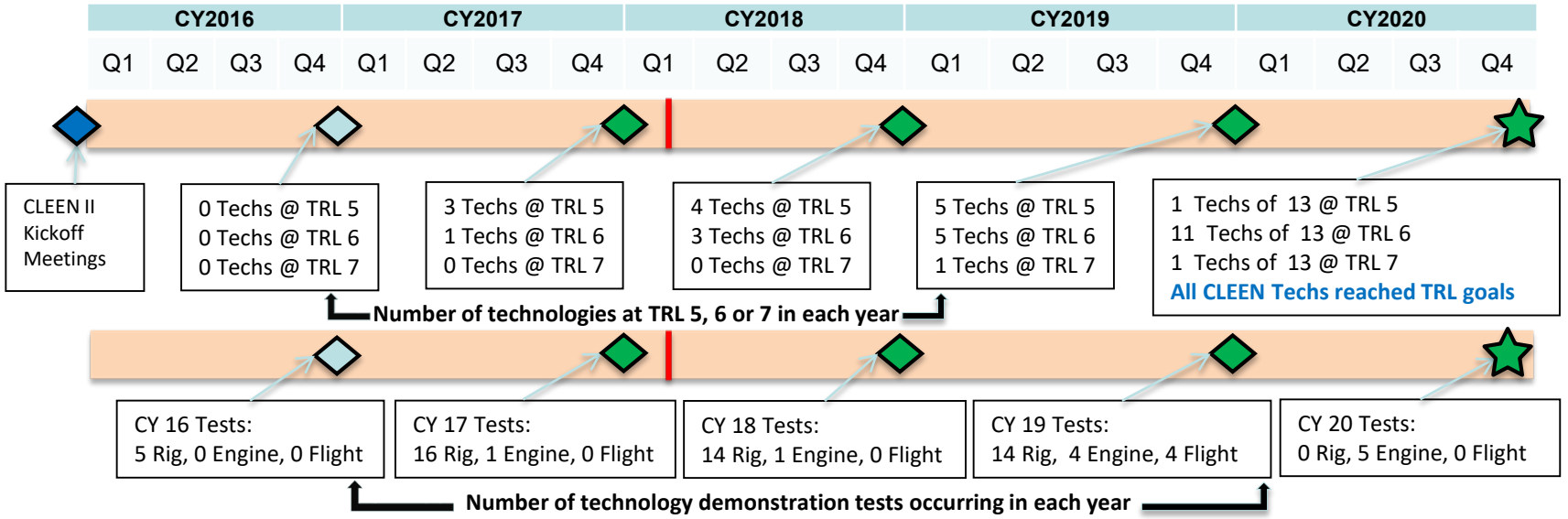
DC-8, 1958

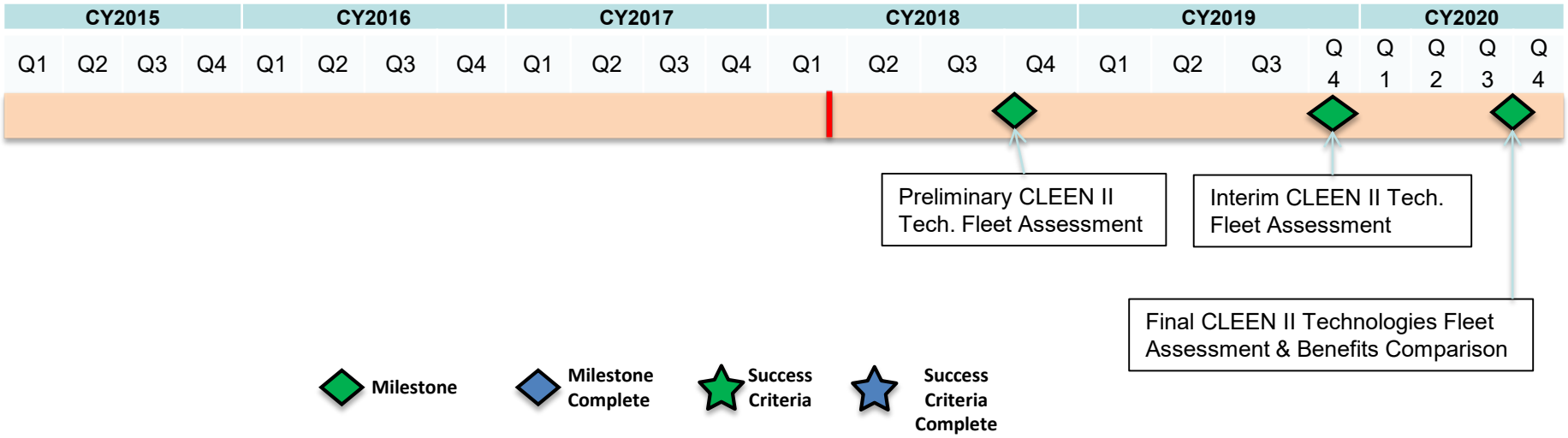
Boeing 787, 2012

- 50% reduction in CAEP Nitrogen Oxides (NOx) emissions standard since 1995
- CLEEN Program - Low NO_X Combustors
  - GE TAPS II Combustor,
    LTO NOx: 55% below most recent CAEP std
    PM: 90% below CAEP visibility smoke limit
  - CLEEN II combustor development ongoing with GE, Honeywell, and Rolls Royce

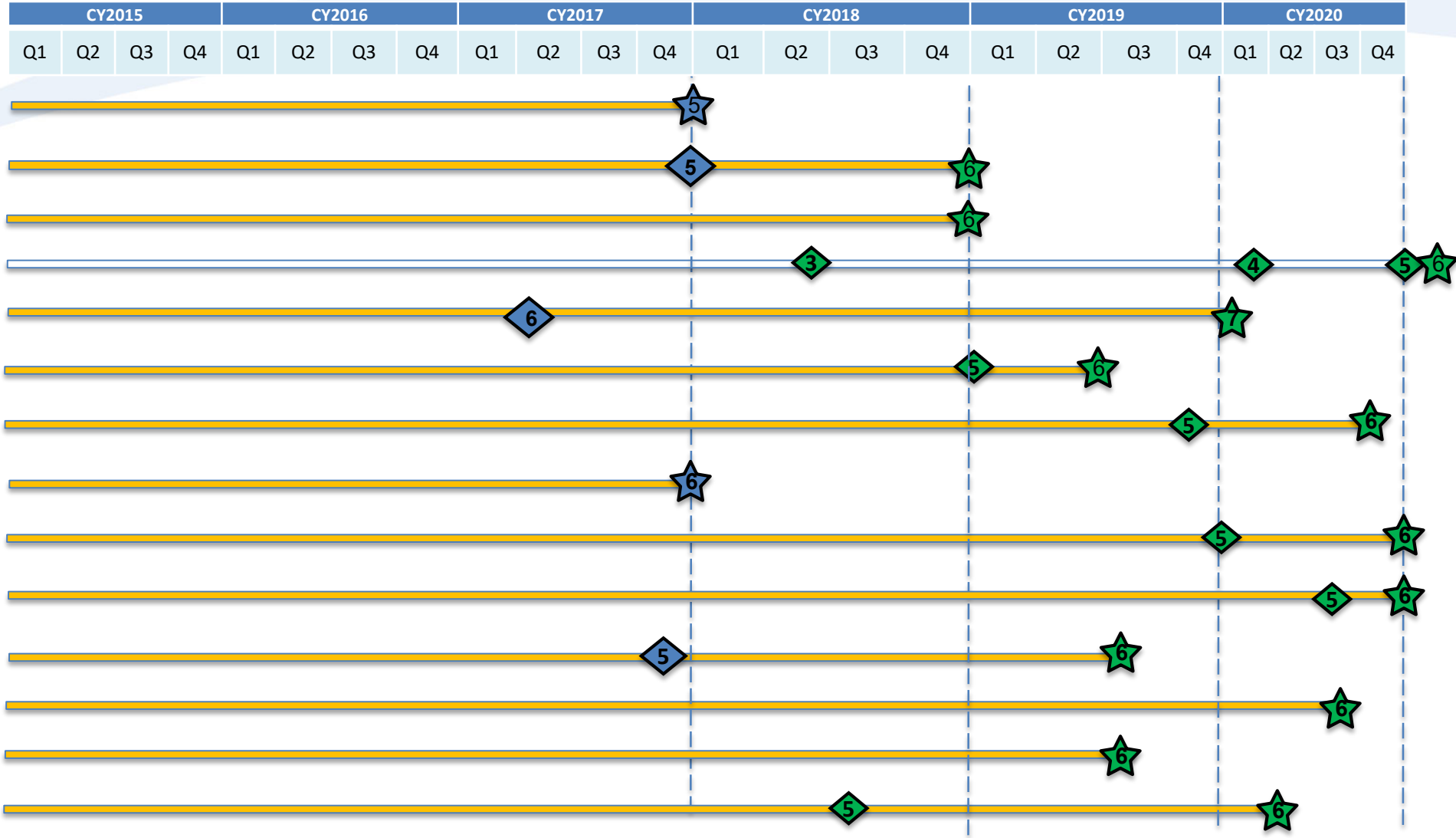


Demonstrating New Technologies Under CLEEN Phase II





CLEEN II Technologies – TRL Milestones



FAA

NextGEN

CLEEN Phase II Progress Highlights

Highlights of completed milestones achieved to date

- Aurora: Y-joint test demonstration
- GE: TAPS III Combustor CLEEN II Technology Program completed 1Q2018 and projected to meet or beat CLEEN II LTO NOx target of 65% CAEP/8 @ 55 OPR. A version of the TAPS III combustor is scheduled to enter into service on the GE9X engine / 777X aircraft in 2020.
- Honeywell: Combustor rig testing is underway
- P&W: Compressor Aero-Efficiency Technologies rig testing
- Rolls Royce: Initial fuel spray nozzle and initial flame tube testing
- UTAS: Achieved TRL5 for two acoustic technologies

Highlights of progress anticipated in 2018

- Boeing: SEW Wing Component Test Article, TRL 6 full-scale test demonstration (Q3 CY 2018)
- Delta Tech Ops; MDS Coating Technologies; America's Phenix: Flight Evaluation of Fan Blade Leading Edge Protective Coating

Ideal Timeline for 3rd Phase of CLEEN

(based on CLEEN Phase 2 timeline and work starting in summer 2020)

2018

2019

May	June ...	Oct ...	Nov	Dec	Jan	Feb	... May	.... Jul	Aug	Sep	Oct	Nov	Dec
FAA Leadership Buyin Market Survey		Draft Solicitation Released		Industry Day in Wash DC		FAA CFO Approval			CLEEN III Solicitation (SIR) Released		CLEEN III Solicitation Closes		Proposals Reviews

2020

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
Proposals Reviews (cont.)		Contract Negotiations Award(s) Announced to individual companies as they are negotiated		Terms & Conditions		Press Release For CLEEN III Awards							

Actual timeline is in flux due to budget uncertainty

In Summary

- CLEEN technology development and alternative fuels projects are progressing under second phase of CLEEN

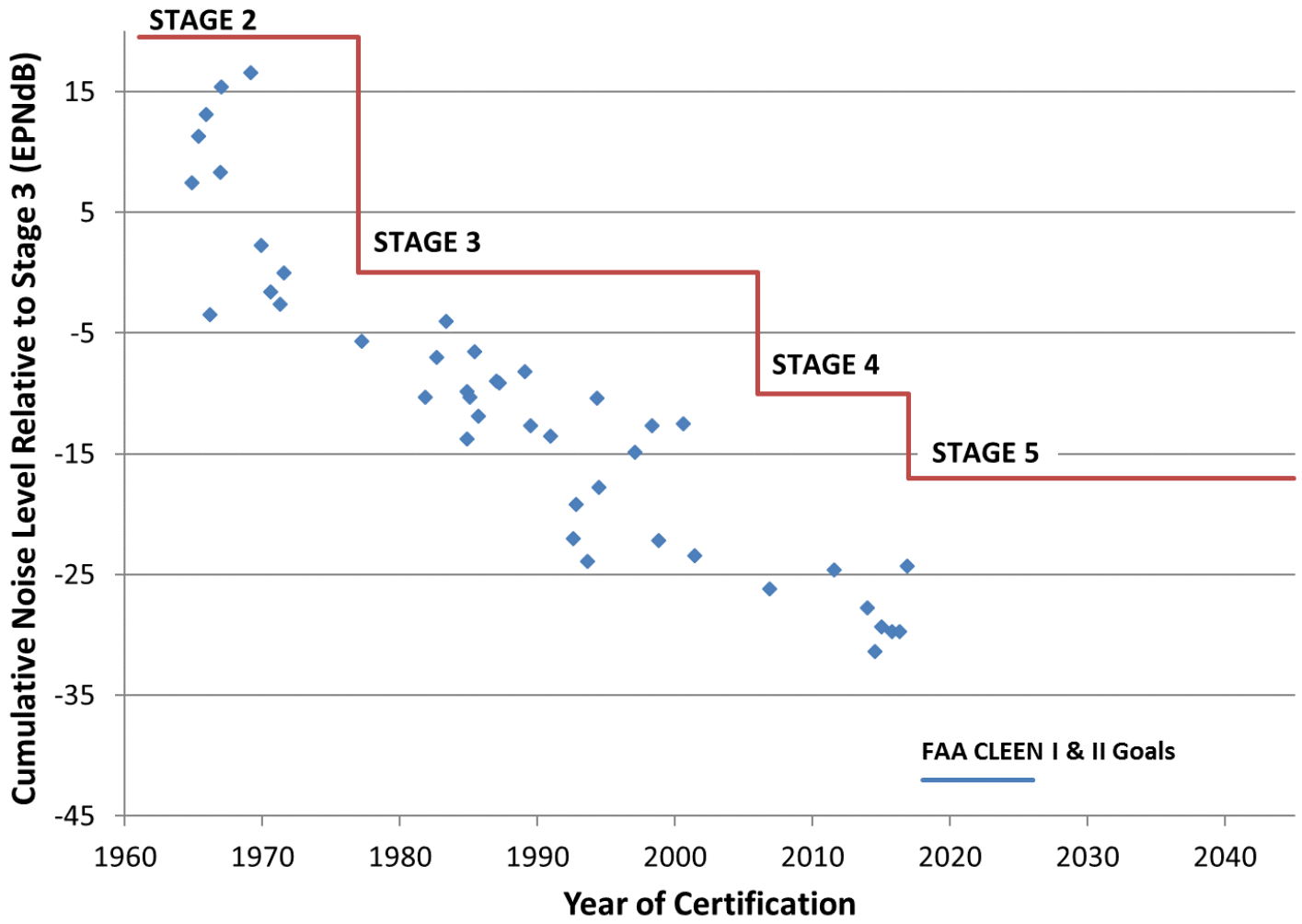
- Coming CLEEN Consortium Meetings:

  May 1-3; Chula Vista, CA
  Nov 6-8; Washington, DC

- In the process of securing support for and initiating planning for 3rd Phase of CLEEN (2020-2025)
- For more on CLEEN https://www.faa.gov/go/cleen

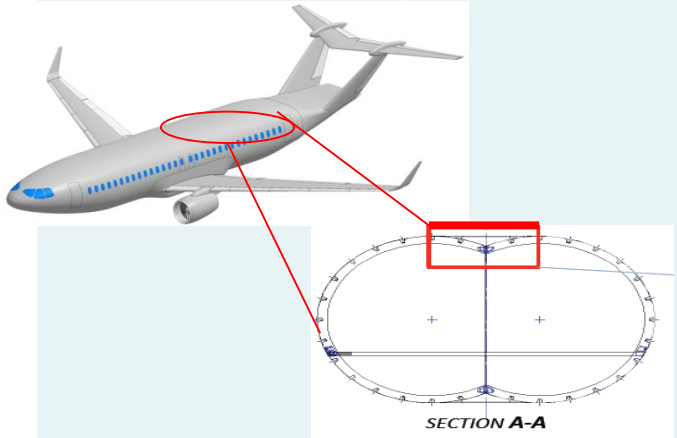
Backup

CLEEN Goal in Relation to Noise Trends

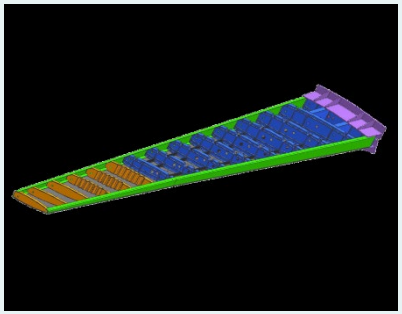


Aurora CLEEN II Technologies

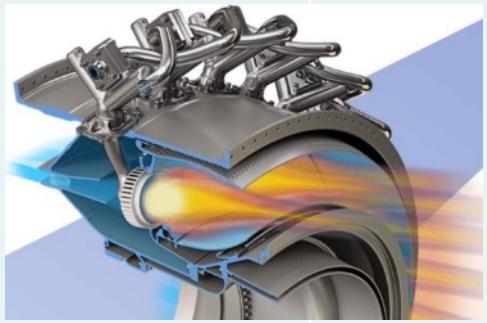
Technology	Goal Impact	Benefits and Application	Key Milestones
D8 aircraft fuselage: Advanced composite structure and Y-joint demonstration	Fuel burn, Noise	29% fuel burn reduction and 16 EPNdB cumulative noise reduction benefits for 2025 with wing mounted engines. 56% fuel burn reduction and 32EPNdB cumulative noise reduction benefits with 2035 technology and integrated engines.	• Y-joint test demonstration – Completed December 2017 • CLEEN II Efforts Completed



Boeing CLEEN II Technologies (1 of 2)

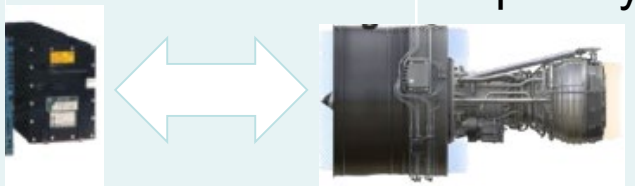
Technology	Goal Impact	Benefits and Application	Key Milestones
Structurally Efficient Wing - enabled by advanced manufacturing and composites technologies	Fuel Burn	Lower weight, higher performance wing, reducing fuel burn by 3.5% 	• CoDR – Completed March 2016 • PDR – Completed January 2017 • DDR – Completed July 2017 • Wing Component Test Article, TRL 6 full-scale test demonstration (Q3 CY 2018)

GE CLEEN II Technologies (1 of 3)

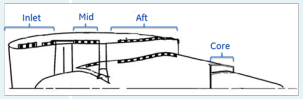
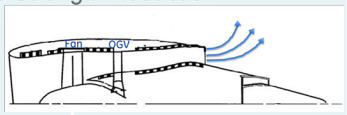
Technology	Goal Impact	Benefits and Application	Key Milestones
TAPS III Low-NOx Combustor Development 	Emissions	65% of CAEP/8 NOx @ 55 OPR – large twin aisle class aircraft	• Combustion dynamics models developed & validated against rig data (April 2017) • Analytical screening (pre-test predictions) of alternate concepts completed (August 2017) • Single-cup rig emissions and P4' screening of the alternate concepts; TRL3 review completed (November 2017) • TAPS III Combustor CLEEN II Technology Program completed 1Q2018; projected to meet or beat CLEEN II LTO NOx target of 65% of CAEP/8 @ 55 OPR. A version of the TAPS III combustor scheduled to enter into service on the GE9X engine / 777X aircraft in 2020.

GE CLEEN II Technologies (2 of 3)

	Benefits and Application	Key Milestones
Flight Management System (FMS) – Engine Integration	Up to 1% fuel burn reduction	• PDR (Q2 CY 2018) • DDR (Q4 CY 2018) • TRL 6 FMS & EFB prototype (Q1 2019)

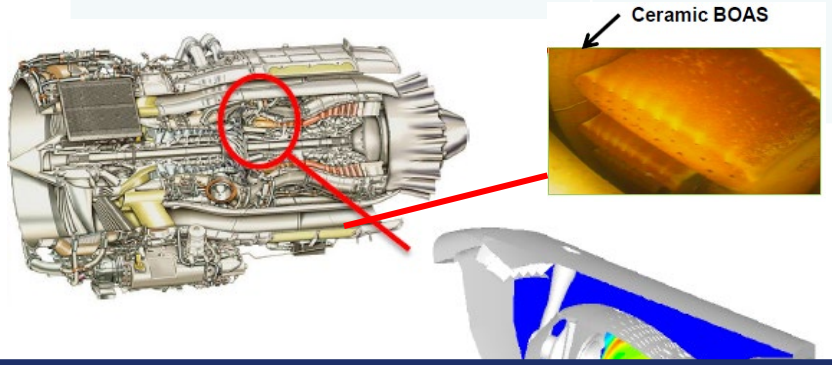


GE CLEEN II Technologies (3 of 3)

Technology	Goal Impact	Benefits and Application	Key Milestones
Low Pressure Ratio Advanced Acoustics *Novel Liners*  *Fan Source Strength Reduction*  	Noise	Liner Noise Benefit ~2EPNdB Cum Fan Noise Source Strength Reduction Noise benefit ~2+ EPNdB	• Fabricated Novel Liner Panels • Initiated Aeroacoustic Design - Q1 2018
Alternative Jet Fuel Test and Evaluation	Alternative Fuels	Testing of drop-in alternative jet fuels to support NJFCP and ASTM International approval	• Full Annular Rig tests; focus on operability impacts • NJFCP fuel (100% Gevo ATJ-SPK) - Completed; • 100% synthetic (HEFA SPK + Virent SAK) (CY2018); • HFP-HEFA blend (CY2018)

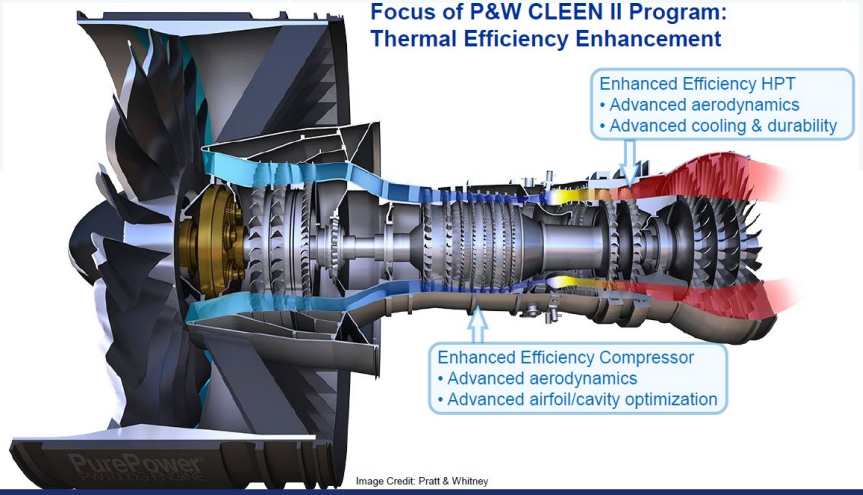
Honeywell CLEEN II Technologies

Technology	Goal Impact	Benefits and Application	Key Milestones
Compact Combustor System	Emissions, Fuel burn	+50% margin to ICAO CAEP/8 NOx Reduced weight, emissions	• PDR Completed • DDR (Q4 CY 2018) • TRL 6 engine test (CY 2020)
Advanced Turbine Blade Outer Air Seal	Fuel burn	Contributes to package that delivers 22% fuel burn reduction vs. in service baseline	• PDR Completed • DDR (Q4 CY 2018) • TRL 6 engine test (CY 2020)

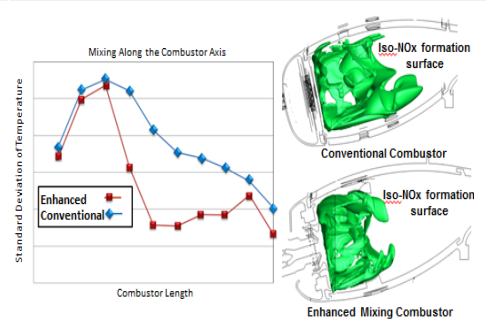


Pratt & Whitney CLEEN II Technologies

Technology	Goal Impact	Benefits and Application	Key Milestones
Compressor Aero-Efficiency Technologies	Fuel burn	0.8-1.0% fuel burn reduction	• Rig tests (Q3-4 CY 2016) Complete • Redesign cycle (CY 2017) • Engine test (CY 2019)
Turbine Aero-Efficiency and Durability Technologies	Fuel burn	0.8-1.0% fuel burn reduction	• Baseline rig tests ongoing • Technology blade rig tests (CY 2018)



Rolls-Royce CLEEN II Technologies

Technology	Goal Impact	Benefits and Application	Key Milestones
Advanced Rich Quench Lean (RQL) Low NOx Combustion System	Emissions	65% margin to ICAO CAEP/8 NOx 	• Initial fuel spray nozzle and initial flame tube testing (Completed) • Full annular rig testing (CY 2017 – 2018) • Engine test (CY2019)
Alternative Jet Fuel Test and Evaluation (Area A)	Alternative Fuels	Testing of drop-in alternative jet fuels to support ASTM International approval	• Alternative fuels testing and demonstration; 100% synthetic (LanzaTech ATJ with Swift mesitylene aromatic) (CY 2017- 2019)

Rohr / UTAS CLEEN II Technologies

Technology	Goal Impact	Benefits and Application	Key Milestones
Short, Integrated Fan Duct Thrust Reverser	Fuel burn	~1.0%	• Achieved TRL5 for two acoustic technologies • PDR (CY 2018) • DDR (CY 2018) • TRL 6 engine ground test (CY 2019)
Advanced Acoustics	Noise	~2.5 EPNdB noise reduction*	

* to offset short fan duct

Legacy Thrust Reverser Fan Duct

CLEEN II Thrust Reverser Fan Duct